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The influence of different photometric observers on luxmeter accuracy for LEDs and FLs lamps measurements

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Age-dependent changes in human eye spectral sensitivity play an important role in contemporary lighting research. Nowadays lighting designing practices take into account the fact that an illuminance level perceived by a given observer depends also on his age. According to recommendations of the International Commission on Illumination CIE presented in the document 227:2017, users age should be taken into account in lighting design of public buildings. The natural consequence of this approach in designing should be the fact that the age of a user also should be considered when verification of lighting installation photometric parameters is performed. According to recommendations of latest CIE documents, verifications of illuminance levels are performed by luxmeters whose spectral sensitivity matches the CIE standard photometric observer $V(\lambda)$ function. At present there is a lack of papers describing how the accuracy of illuminance measurements could be affected by the fact that with age there are changes in human eye spectral sensitivity and it differs from $V(\lambda)$ function. To fill this gap we present in this article results showing how applying of different photometric observers influence the luxmeter accuracy. The calculations were performed for LED and FL light sources measured by class B and class C luxmeters. These results indicate that a luxmeter error f_1 strongly depends on correlated color temperature of a lamp under measurement and spectral sensitivity of applied photometric observer.

Keywords: lighting technology, photometry, illuminance.

1. Introduction

Nowadays, light measurements have become a popular practice in many places, because poor lighting can lead to eye-strain, fatigue, headaches, stress and accidents. On the other hand, too much light can also cause safety and health problems such as “glare” headaches and stress. In many countries, employers [1] and managers of public buildings are obligated by regulations to assess interior lighting quality [2, 3] by measurements of illuminance. The popular way of illuminance measurements is using an illuminance meter (luxmeter). The luxmeter should quantify the intensity of light like it is perceived by the human eye at a given area [4]. This means that spectral sensitivity of those measurement instruments must match up with spectral sensitivity of human observers.

The human eye does not process with equal efficiency all particular wavelengths of radiation entering it. This means that there is no constant eye spectral sensitivity for each wavelength and the spectral sensitivity is described by the spectral efficiency function. The International Commission on Illumination CIE (an international standardizing body for illumination) in 1924 defined a photopic luminous efficiency function – a standard spectral sensitivity function appropriate for targets that subtend a 2° visual angle (this angle was chosen owing to the belief that the color-sensitive cones resided within a 2° arc of the fovea). Following this, in 1931, CIE basing on a series of experiments done in the late 1920s by GUILD [5] and WRIGHT [6], introduced a photopic luminous efficiency function (Fig. 1) called the 2° standard photopic luminous efficiency function, known also as a standard human eye sensitivity function CIE 1931 $V(\lambda)$. In 1964 CIE established a supplementary standard observer function for 10° observer. It was derived from the work of STILES and BURCH [7] and SPERANSKAYA [8]. This was the next step in research on a human eye spectral sensitivity function CIE described in the document 86:1990 [9]. This standard provides data concerning spectral luminous efficiency function for photopic vision called the modified 2° spectral luminous efficiency function for photopic vision $V_M(\lambda)$. In the 21st century the population ratio of the elderly to young is increasing quite rapidly [10] and lighting designers take a challenge for proper lighting design of the places where elderly people are staying, *i.e.* nursing homes. It is well known that the age related changes of the crystalline lens produce modifications of the spectral characteristics of the light arriving at the retina of older people [11]. Through the life span, there is a reduction in retinal sensitivity particularly

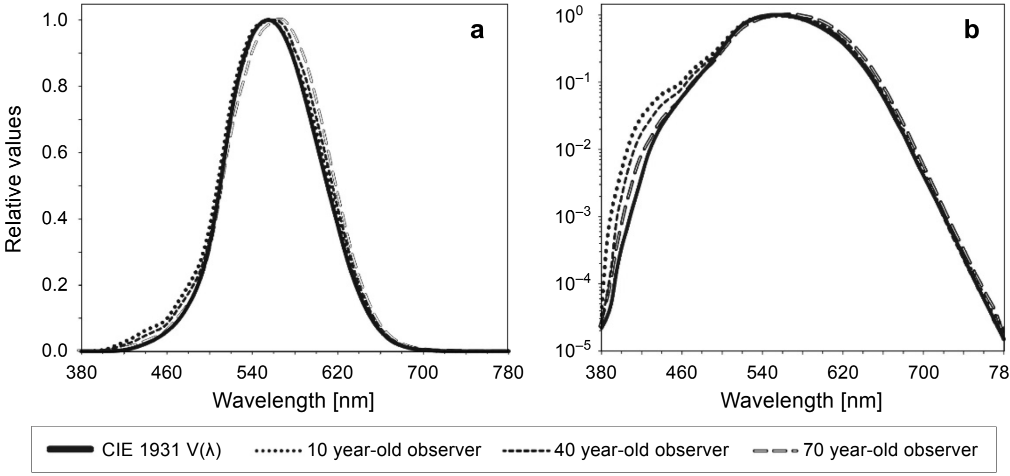

Fig. 1. The CIE $V(\lambda)$ standard photometric observer function and relative spectral sensitivity of human eye for 10, 40 and 70 year-old person in linear (**a**) and logarithmic (**b**) scale.

at short wavelengths. A limited number of quantitative data on how much the sensitivity decreases with age across the visible spectral range was reported by Kraft and Werner [12]. In 2001 Sagawa and Takahashi [13] where summarized data for eye spectral sensitivity for different age persons. Figure 1 presents data of relative spectral sensitivity of human eye for 10, 40 and 70 year-old person in a linear scale in Fig. 1**a** and logarithmic scale in Fig. 1**b**. Basing on those data, it could be expected that an illuminance level and color seen by older people are different from that seen by young people. For this reason, CIE in the document 227:2017 [14] gives guidelines how to design appropriate visual environment for people with low vision. Basing on existing visual models, the document also determines recommendations for illuminance levels for elderly people.

The other main issue in lighting projects is verification of illuminance levels for a given installation. Lighting designs are carried out by using a maintained illuminance method, which aims to provide not less illuminance value than required task illuminance. The measurements of task plane illuminance are used to assess whether the installation performance meets specification. The average measured illuminance should never be lower than the average maintained illuminance. According to standards, verification of an illuminance level in public places must be performed by luxmeters which meet the criteria described in ISO/CIE 19476:2014 [4]. According to those documents, the spectral sensitivity of a luxmeter must match $V(\lambda)$ function [4, 15].

2. Factor for describing spectral sensitivity match of luxmeter to $V(\lambda)$ function

There is a wide range of illuminance measurement equipment available for use in lighting measurements. The state of the art luxmeteres are equipped with silicon detectors. The spectral sensitivity of this type of detectors (Fig. 2) largely deviates from the $V(\lambda)$ function. For this reason, the detectors in luxmeters have to be adapted to $V(\lambda)$ function by using glass filters placed on their front. However, due to technological limitations in filters and their production tolerances, in practice it is not possible to get an absolute match to $V(\lambda)$ function and there is a deviation of luxmeter spectral sensitivity $S(\lambda)$ from it (Fig. 2). The quality of the luxmeter spectral matching to $V(\lambda)$, according to document ISO/CIE 19476:2014 [4], is described by integral parameter f_1' known as a luxmeter spectral correction error,

$$f_1' = \frac{\displaystyle\int_{380}^{780} \left| \frac{\displaystyle\int_{380}^{780} P_{\mathrm{A}}(\lambda) V(\lambda) \mathrm{d}\lambda}{\displaystyle\int_{380}^{780} P_{\mathrm{A}}(\lambda) S(\lambda) \mathrm{d}\lambda} S(\lambda) - V(\lambda) \right| \mathrm{d}\lambda}{\displaystyle\int_{380}^{780} V(\lambda) \mathrm{d}\lambda} \times 100\% \tag{1}$$

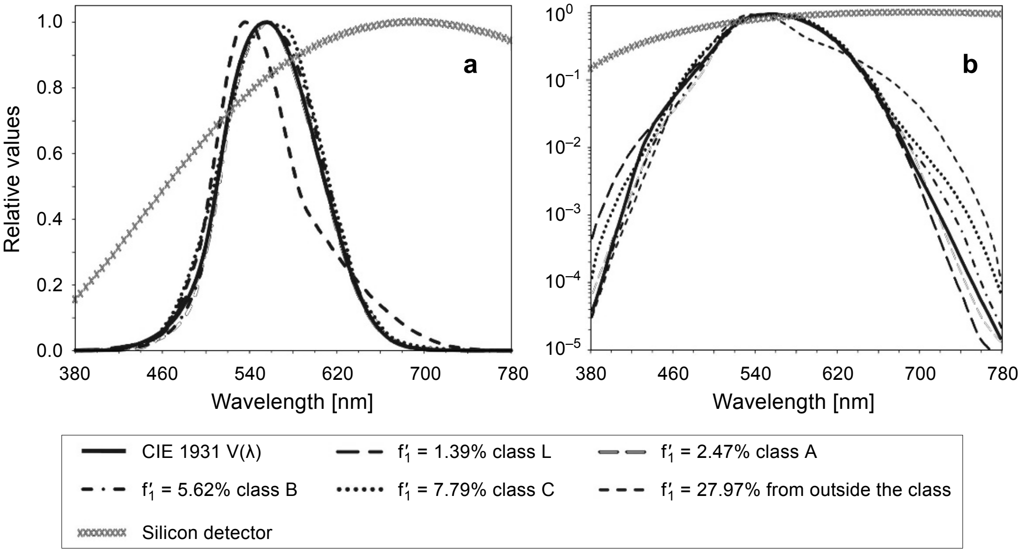

Fig. 2. The $V(\lambda)$ standard photometric observer function and relative spectral sensitivity of commercially available luxmeters and silicon detector sensitivity in linear (**a**) scale and logarithmic (**b**) scale.

where: $P_A(\lambda)$ – relative spectral power distribution (SPD) of illuminant A (luxmeter calibration source), $V(\lambda)$ – relative spectral sensitivity of CIE standard photometric observer, $S(\lambda)$ – relative spectral responsivity of luxmeter.

Based on f_1' value, the luxmeters are categorized into four different quality classes depending on the degree of deviation (the Table).

Table. Classification of luxmeters according to spectral matching quality [4].

Luxmeter classification	Class L	Class A	Class B	Class C
The maximum value of error f_1'	≤ 1.5%	≤ 3%	≤ 6%	≤ 9%

Out of class instruments cannot be used in proper measurements of illuminance. Type L and A luxmeters which are of high accuracy are used in laboratory measurements. For lighting level verifications generally are used class B or class C luxmeters.

Luxmeters could be used to measure any type of light sources (Fig. 3), even narrowband or unfavorably spectral distributed light, *e.g*. FL or LED lamps, but the f_1' value describes only the quality of spectral matching when illuminant A (incandescent bulb with correlated color temperature CCT = 2856 K) is used for illumination. The luxmeter inaccuracy for measurements other than standard A illuminant light sources (Fig. 3) can be significant if the SPDs of a lamp coincides with a luxmeter spectral responsivity $S(\lambda)$ (Fig. 2) region with a significant mismatch from the $V(\lambda)$ response function. Due to this fact, the value f_1' cannot be applied as measurement uncertainty or correction

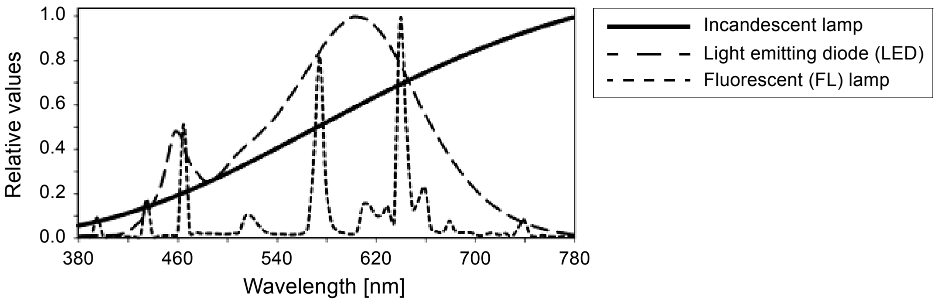

Fig. 3. Relative spectral power distribution of incandescent, FL and LED type lamps.

factor for luxmeters. The International Commission on Illumination in its documents introduced the quantity which describes a luxmeter error resulting from differences between the measured and the calibration lamps light spectral distribution.

3. The luxmeter error resulting from differences in the measured and calibration light source spectral power distribution

The parameter f_1 is used [4] for describing a luxmeter error resulting from differences in the spectral power distribution of the measured and calibration source (illuminant A)

$$f_1 = \frac{\dfrac{\int_{380}^{780} P_\mathrm{S}(\lambda)S(\lambda)\mathrm{d}\lambda}{\int_{380}^{780} P_\mathrm{S}(\lambda)V(\lambda)\mathrm{d}\lambda} - \dfrac{\int_{380}^{780} P_\mathrm{A}(\lambda)S(\lambda)\mathrm{d}\lambda}{\int_{380}^{780} P_\mathrm{A}(\lambda)V(\lambda)\mathrm{d}\lambda}}{\dfrac{\int_{380}^{780} P_\mathrm{A}(\lambda)S(\lambda)\mathrm{d}\lambda}{\int_{380}^{780} P_\mathrm{A}(\lambda)V(\lambda)\mathrm{d}\lambda}} = \frac{\dfrac{\int_{380}^{780} P_\mathrm{S}(\lambda)S(\lambda)\mathrm{d}\lambda}{\int_{380}^{780} P_\mathrm{S}(\lambda)V(\lambda)\mathrm{d}\lambda}}{\dfrac{\int_{380}^{780} P_\mathrm{A}(\lambda)S(\lambda)\mathrm{d}\lambda}{\int_{380}^{780} P_\mathrm{A}(\lambda)V(\lambda)\mathrm{d}\lambda}} - 1$$

$$= k - 1 \tag{2}$$

where $P_\mathrm{A}(\lambda)$ denotes the spectral power of illuminant A, the parameter k is the correction factor

$$k = \frac{\int_{380}^{780} P_\mathrm{S}(\lambda)S(\lambda)\mathrm{d}\lambda}{\int_{380}^{780} P_\mathrm{S}(\lambda)V(\lambda)\mathrm{d}\lambda}\,\frac{\int_{380}^{780} P_\mathrm{A}(\lambda)V(\lambda)\mathrm{d}\lambda}{\int_{380}^{780} P_\mathrm{A}(\lambda)S(\lambda)\mathrm{d}\lambda} \tag{3}$$

and k value can be used for calculating the real value of illuminance E_{R} created by any light source. The E_{R} value is obtained by multiplying the illuminance E_{M} indicated by the luxmeter by the correction factor k

$$E_{\mathrm{R}} = k E_{\mathrm{M}} \tag{4}$$

By performing costly calibrations, leading luxmeters manufacturers included information on the correction factor k value in datasheet of their products, but for cheap luxmeters those data are not provided. Typically, sets of k values are given for standard lamps, *e.g.* a set of twenty fluorescent light sources defined by the CIE in document 15:2004 [16]. Those lamps have various spectral compositions and their SPDs (Fig. 4) are published in the CIE document 15:2004 [16]. In this CIE document those lamps are numbered from FL1 to FL12 and their correlated color temperature CCT covers the range from warm white light (2940 K) up to cold white light (6500 K). Lamps from FL1 to FL6 consist of two semi-broadband lines of spectral emissions. The broadband lamps are with numbers from FL7 up to FL9. Those lamps are with multiple phosphors and higher color rendering index (CRI). Opposite to their spectra are triband illuminants – lamps with numbers FL10, FL11 and FL12 which have narrowband emissions in the red, green and blue regions of the visible spectrum.

According to the fact that nowadays in lighting designs the observers' age should be taken under account [14], it is also important to consider the age of observers when

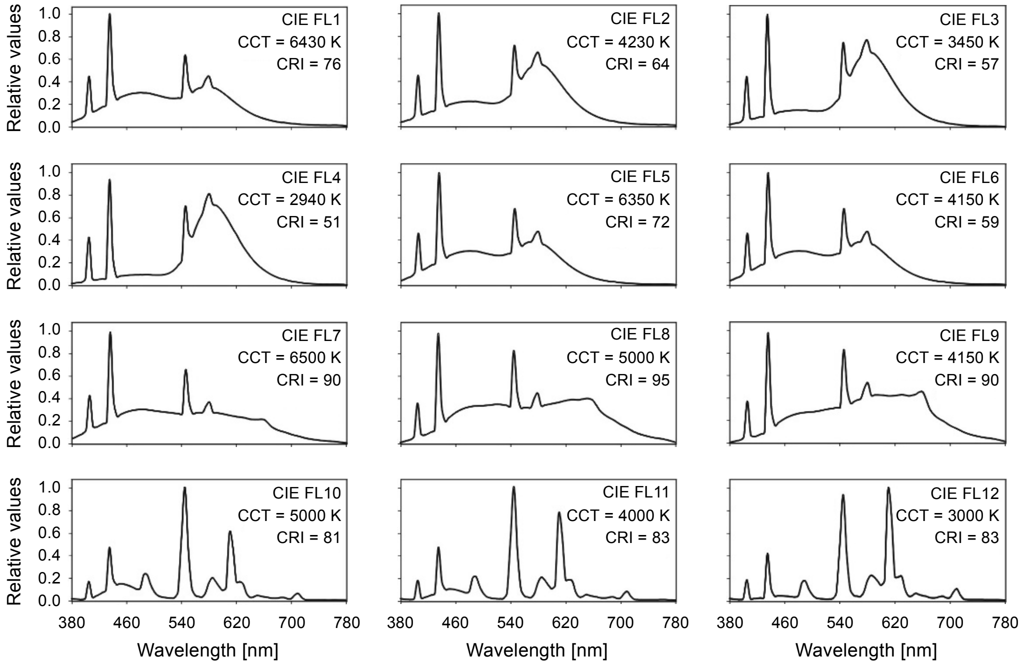

Fig. 4. Relative spectral power distributions of standard fluorescent lamps [16].

the measurement verification of photometric parameters for lighting installations is performed. The illuminance level perceived by a given observer, due to the difference between his/her spectral eye sensitivity (Fig. 2) and the $V(\lambda)$ function, differs from that measured by a luxmeter, even when the factor k for the measurement of a given lamp was applied.

4. The illuminance measurement accuracy for different photometric observers

To calculate how different photometric observers influenced the luxmeter accuracy, some calculations were performed for typical luxmeters used in lighting quality inspection (class B and class C). The spectral power distributions of standard FL lamps (Fig. 4) and typical in market LED lamps were considered. The LED lamps lighting parameters including their SPDs are shown in Fig. 5. Their correlated color temperature CCT covers up the range from warm white light (2862 K) to cold white light (6273 K). The range of their CCT is similar to CCT of standard FL lamps.

Figure 6 presents the luxmeter error f_1 and correction factor k values *vs*. lamp correlated color temperature CCT (FL and LED) for measurements performed by a class B ($f_1' = 5.62\%$) and C ($f_1' = 7.79\%$) luxmeters. These calculations were done for four different photometric observers (mimicking standard photometric observers $V(\lambda)$ data and human eye spectral sensitivity data for a 10, 40 and 70 year-old person).

In a class B luxmeter, the value of error f_1 and correction factor k strongly depends on lamp correlated color temperature CCT (for both FL and LED) for all ages of observers. For the cold white light FL lamps and the cold white light LED lamps (CCT around 6500 K), the luxmeter error f_1 for $V(\lambda)$ standard photometric observer is on the level

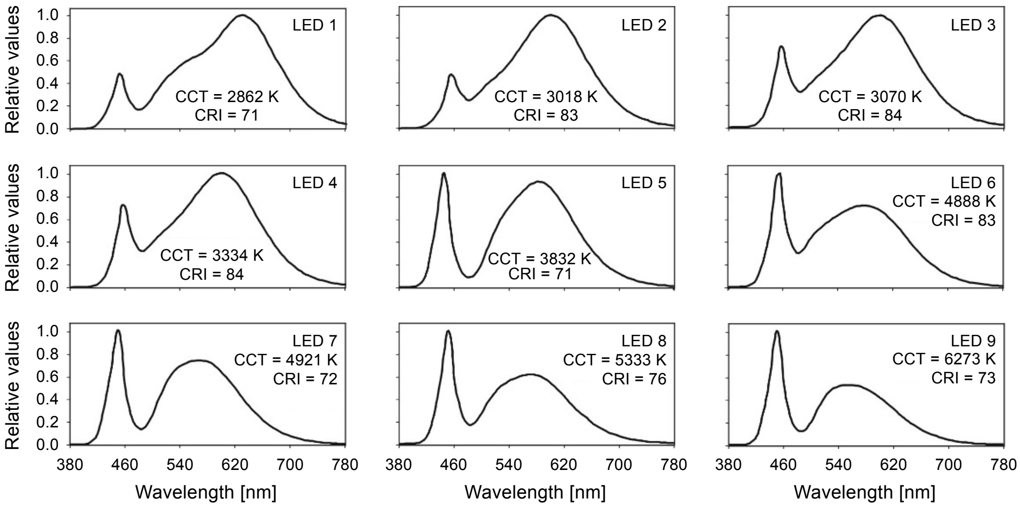

Fig. 5. Relative spectral power distributions of typical indoor LED lamps.

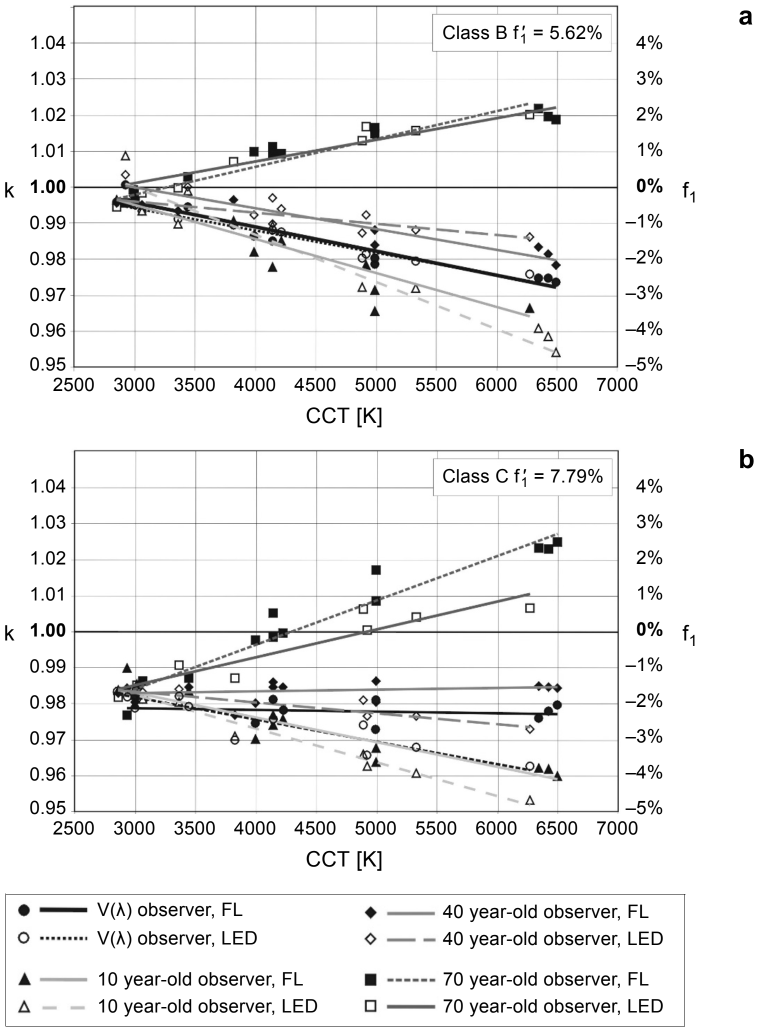

Fig. 6. Class B (**a**) and class C (**b**) luxmeter correction factor *k* and error f_1 values *vs*. the lamp correlated color temperature CCT.

of –3%, but when a 40 year-old observer will be taken under consideration, the error decreases slightly by about 1% up to around –2% value. For a 10 year-old observer, the luxmeter error f_1 will reach the level of –5% for cold white light LED lamps and –4% for cold white light FL lamp. But when the same luxmeter will be used for illuminance evaluation according to 70 year-old person eye spectral sensitivity, the value of the error f_1 will change character and reach the level about +2% for cold light FL and LED lamps. This means that differences between the 10 and 70 year-old person in illuminance reception will reach 7%. As was written before, to get the correct value of illuminance, the luxmeter reading must be multiplied by the correction factor k. In the case of cold white FL lamps, the reading will be multiplied by 0.975 for a $V(\lambda)$ standard photometric observer but when 70 year-old photometric observer is taken under consideration, the correction factor k is 1.020. In result, this difference causes 4.5% error in determining the illuminance value.

In a class C luxmeter, its error f_1 and correction factor k value for $V(\lambda)$ observer and a 40 year-old observer are on the constant level (about 2% and 0.98, respectively) which is practically independent of lamp correlated color temperature CCT. For a 10 and 70 year-old observers the value of the luxmeter error f_1 and parameter k strongly depends on lamp CCT and for cold white light FL lamps its value is reaching the level of +3% for a 70 year-old observer (+1% for cold white light LED lamp). For a 10 year-old observer, the luxmeter error f_1 is about −4% for cold white FL lamps and –5% for cold white light LED lamps. Additionally, the value of the luxmeter error f_1 is equal to 0 when LED or FL lamps having CCT between 4000 and 5000 K are measured and a 70 year-old photometric observer is taken in place of a standard photometric observer. This fact can be beneficial because for getting a proper illuminance value from that class C luxmeter its E_M reading value indicated by a luxmeter does not need to be corrected by any correction factor k value.

5. Conclusions

In proper verification of illuminance levels, in contemporary designed public spaces, the newest discoveries on the eye spectral sensitivity should be applied to illuminance measurements performed by luxmeters. This paper shows that there is an influence of different photometric observers on illuminance measurement accuracy performed by contemporary luxmeters. This influence was described by the luxmeter error f_1 value and the luxmeter correction factor k value. The results presented in this paper proved that a relatively not expensive class C luxmeter can have a good measurement accuracy of cold white light both LED and FL lamps when a 70 year-old observer is taken under consideration in place of a standard photometric observer $V(\lambda)$. This fact is very important because lamps emitting cold light are installed in hospitals, offices and other public places, where many elderly people stays. Basing on the presented research, it is possible to say that illuminance level evaluation in these kinds of places could be easily done without using the luxmeter calibrations factors k which are provided only by calibration laboratories – involving additional costs. On the other hand, for young photometric observers, taken in the place of the CIE standard photometric observer, the luxmeter error f_1 is significantly higher than for standard $V(\lambda)$ photometric observers taken under consideration for a class C luxmeter.

The luxmeter error f_1 is equal to 0 for a class B luxmeter, when a 70 year-old photometric observer and warm white light lamps (CCT about 3000 K) are taken under consideration. For cold white lamps, the luxmeter error f_1 for this observer is of about the same absolute value that for standard $V(\lambda)$ observer but with an opposite sign. As a result, when the correction factor k for a class B luxmeter and standard CIE $V(\lambda)$ photometric observer will be applied in measurement data, the measurement error will double.

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